2.0 AN OVERVIEW OF DAMS

2.1 DAMS IN INDIANA


Figure 2-1 Earth embankment dam in Indiana.

A dam is a man-made barrier constructed for the purpose of storing or diverting water. The barrier is usually constructed across a watercourse such as a stream or river, and usually consists of earthen materials or concrete. There are more than 1,200 dams in Indiana, including approximately 250 high hazard dams. Most dams in Indiana are earth embankment dams less than 50 feet high, and typically are used for recreation, flood control, and water supply. Some dams store water to harness its force to generate electricity. Many of the existing dams in Indiana are relatively old (30 years or more), making dam safety inspections and maintenance an important part of their operation plan.

Every dam should accomplish the following objectives under all anticipated loading conditions:

(1) hold back or store water safely
(2) contain the water and resist leakage
(3) maintain its shape and configuration
(4) resist movement in any direction
(5) safely pass maximum design flood events

The water stored behind the dam imposes significant forces on the embankment and foundation materials. The pressures exerted on the dam and its foundation increase as the depth of stored water behind the dam increases, thus requiring greater resistance to leakage and movement. The pressure of the stored water loads the dam such as to tend to push the dam downstream, creating the potential for stability problems. Therefore, greater water depths require wider, stronger dams. Resistance to leakage is important since the purpose of the dam is to store water. Once leakage starts, it can get progressively worse with time and can create a safety hazard and eventually cause dam failure. The function of maintaining the shape is more related to dams constructed of earth material or rock than those made of concrete. The shape refers to the outline of the dam or the profile along the centerline. The final shape of the dam is usually dictated by the type and amount of material necessary to resist leakage and movement. If the shape of the dam changes, it may no longer be able to perform its required functions and may become a safety hazard. External forces, such as earthquakes and extreme weather events can also affect and change the ability of a dam to perform its functions. Therefore, dams must be properly designed and maintained to withstand all conceivable forces that may be encountered.

Figure 2-2 is a section through an earth embankment dam illustrating many of the principal components of a typical dam. The dam in the sketch is called a zoned dam since the cross section consists of zones of different materials, including an impervious core and a pervious outer shell. Understanding the purpose of these components is essential to any evaluation of a dam's condition. The following discussion describes the principal components and their purpose.

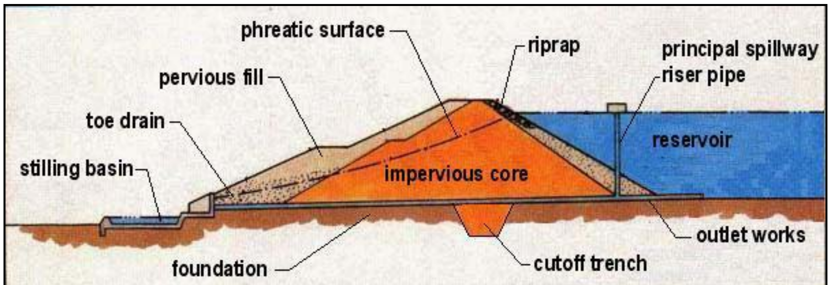

Figure 2-2 Section through a typical embankment dam with a riser pipe used as the principal spillway.

The part of the dam site which must support the dam is the foundation. Although other factors are involved, the first task of the foundation is to provide firm support for the entire dam. A soft foundation, for example, would not support the weight of the dam. Because the main purpose of the dam is storage of water, the foundation must also resist the flow of water under the structure. A clay material or unfractured hard rock, for example, would resist the flow of water under the structure much more effectively than sand or gravel.

Figure 2-3 Upstream slope, downstream slope, crest, and reservoir of an earth embankment dam.

The reservoir is the body of water impounded by the dam. The basin behind the dam or the area covered by the reservoir is just as important as the dam itself. Its size and shape determine the volume of the reservoir. Like the dam, the foundation, and the abutments, the basin must contain the water.

The embankment is the main part of the dam, and is usually referred to as the dam. In Indiana, the embankment usually consists of local soil materials which may vary in quality. Some dams consist of an impervious soil core in the center of the embankment with rock covering (pervious fill) the upstream and downstream slopes to protect the core and to provide strength to the embankment (see Figure 2-2). In the case of a concrete dam, a concrete structure is used instead of an embankment.

The upstream embankment slope is the inclined surface of the dam that is in contact with the reservoir. This slope must be protected from erosion due to waves. Erosion protection may include grass, or the placement of riprap or some other durable material. The crest is the top surface of the dam. Often a roadway is established across the crest for traffic or to facilitate dam operation, inspection, and maintenance. The shoulders are the upstream and downstream edges of the crest. The downstream slope is the inclined surface of the dam away from the reservoir. This slope also requires protection from erosive effects of rain. Grass is often used for erosion protection on the downstream slope. The toe (or downstream toe) is the junction of the downstream slope (or face in the case of a concrete dam) of the dam with the ground surface. Riprap is a layer of stones, broken rock, or precast blocks placed in random fashion on the upstream slope of an embankment dam, on reservoir shores, or on the sides of channels to protect against wave erosion and ice action. Large riprap is referred to as armoring.

The cutoff trench is an excavation in the foundation of a dam for the purpose of construction of a vertical barrier (such as a core or diaphragm) to seepage. Often the core is extended into the foundation by digging a trench along the length of the dam and filling it with the flow-resistant material. Extending the barrier into the foundation to control the flow of water under the dam is important, especially if a porous material such as sand, gravel, or weathered/fractured bedrock lies directly beneath the embankment. If the foundation has low resistance to the flow of water, for instance, through fractured rock or a sand layer, the most effective means of reducing the flow of water through the foundation is a cutoff.

The abutment is that part of the valley side against which the dam is constructed. The contact between the abutment and the embankment slope is called the slope-abutment-interface or groin. The abutments and groins are designated as left or right when facing downstream while standing on the crest of the dam. The abutments must offer support to the structure in the length-wise, upstream-downstream, and vertical directions.

Figure 2-4 Photograph of abutment (right), embankment (left), riprap-lined groin, and spillway outlet.

The spillway is a structure over or through which storm or flood flows are discharged from the reservoir. If the rate of flow is controlled by mechanical means, such as gates, the structure is considered a controlled spillway. Otherwise, the spillway is considered as uncontrolled. The principal spillway is the initial spillway designed to carry the storm or flood discharge. It may be either a drop inlet (riser) or an overflow structure. Usually, the principal spillway is designed to maintain the water in the reservoir at a constant level known as the normal pool. The emergency spillway is designed to safely pass the discharge of large storms or flood flows in conjunction with the principal spillway, thereby preventing the dam from being overtopped and possibly breached. Spillways must be designed and constructed to prevent overtopping of the dam embankment for the anticipated maximum loading conditions. A spillway can be located on either abutment or constructed as part of the dam. Sometimes a natural drainage channel adjoining the reservoir is used to carry floodwater safely around the dam. The location is selected based on the topography, size of expected storm, and economics. The adequacy of an existing spillway requires evaluation by a qualified dam safety professional. Uncontrolled spillways should not be constructed over embankment fill materials.


Figure 2-5 Riprap-lined stilling basin at spillway outlet.

The outlet works are structures (pipes) which are used to drawdown or drain the reservoir. The primary purpose of the outlet works is to provide for controlled release of the water from the reservoir behind the dam. Upon demand, the outlet can be used to release water downstream for irrigation or other uses. The system is also used to lower the reservoir in an emergency or for maintenance and repair of the dam and appurtenant structures. The size of the outlet system is determined by the rate of the demand for use of the water. A valve must be included to regulate the drawdown rate.


Figure 2-6 Toe drain pipe outlet (right) located near principal spillway outlet.

The stilling basin or plunge basin is a basin or pool area at the toe of the dam into which the spillway and outlet works discharge. This area is designed to dissipate the energy of the flow so as to prevent downstream scour or erosion (see Figure 2-5).

The toe drain is a method of controlling the seepage of water through a dam. Water entering the drain should flow freely through the drain and exit safely beyond the dam without wetting the material in the downstream slope. A pipe is often installed in the toe drain to carry the internal seepage water away from the dam to prevent erosion of the soil from the embankment. The collector pipe is usually surrounded by a filter material and placed in the toe of the dam or laid in a trench beneath the toe. Other types of drains may be used to collect seepage water.


Figure 2-7 Trash racks on riser spillway structure.

Appurtenant structures refer to ancillary features of a dam such as outlet works, spillways, powerhouse, tunnels, trash racks, etc. The trash rack is a screening device located at an intake structure to prevent the entry of debris.

2.2 TYPES OF DAMS

Most dams in Indiana are earthfill embankment dams. However, there are a few rockfill and concrete dams. This subchapter briefly describes the characteristics of each of these dam types.

Earthfill Dams

Earthfill embankment dams are by far the most common type of dams. An earthfill dam is defined as an embankment dam in which more than 50% of the total volume is formed of compacted fine-grained soil obtained from a borrow area. Fine-grained soil is a soil material with more than 50% passing the #200 mesh sieve, typically clays. A homogeneous earthfill dam is an embankment dam constructed of similar earth material throughout, except for possible inclusion of internal drains or drainage blankets. Excessive water seeping from the downstream slope of a dam is an unsafe condition that requires remedial measures to correct the situation. Therefore, every effort is made in design of an earth dam to minimize the chance for uncontrolled water to exit on the downstream face.

Many of Indiana’s soils are well suited for embankment dam construction. Fine-grained, cohesive soils (typically clays) that are resistant to water seepage are common. This is the main reason that earth embankment dams are prevalent.

An embankment dam which is composed of zones of selected materials having different degrees of porosity, permeability, and density is called a zoned embankment dam. The zoned dam provides control of the flow of water with a core having a very high resistance to flow. In the case of the zoned dam with a drain, a coarse-grained material is installed to adequately control internal seepage.

Depending on the dam foundation conditions, seepage control under the dam may also be required. Core trenches are often installed under the embankment to control seepage through permeable materials that may be present (e.g. sand, gravel, fractured bedrock). The core trench is typically excavated to a relatively impermeable soil barrier layer and filled with compacted soil that can retard or stop the seepage. Gout curtains, slurry walls, or other types of cutoff walls may also be used to control foundation seepage.

Rockfill Dams

A rockfill dam is an embankment dam in which more than 50% of the total volume comprises compacted or dumped pervious natural or crushed rock. Most rockfill dams are similar in shape to earth dams. The difference is that rock fragments make up the primary material used for construction. The choice of constructing a rockfill dam versus constructing an earth dam is usually based on availability of materials. Because rock fragments alone would leave large openings for seepage flow, a central core, like that in the zoned earth dam, is required. Also, note that the core usually extends into the foundation to help control the flow of water under the dam. A transition zone is usually necessary to protect the core from internal erosion. The transition zone is designed to keep the fine-grained core materials from being washed into or through the rockfill. Gout curtains, slurry walls, or other types of cutoff walls may also be used to control foundation seepage.

Concrete Dams

Concrete dams are the least common in Indiana. Concrete is probably the most durable material for building dams and has a very high resistance to seepage. A concrete dam is unique in that it directly transfers the pressures created by the stored water to the foundation and abutments. A concrete dam, therefore, is dependent upon the ability of the foundation and abutments to hold the dam in place. Like earth or rockfill dams, a concrete dam must have special provisions for controlling seepage under the dam. The most common method is pressure grouting a line of holes into the foundation and abutments before the dam is constructed. The cement grout will fill most voids or fractures in the rock.

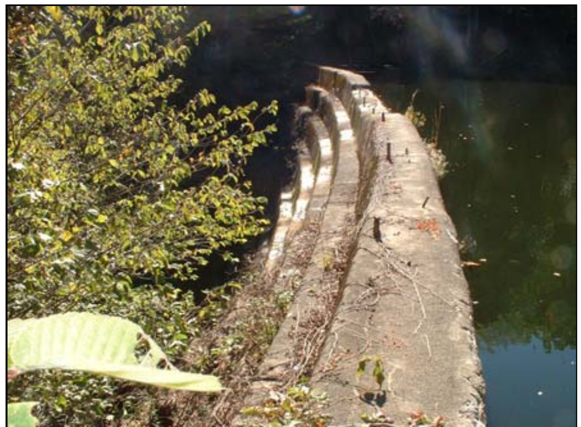

Figure 2-8 A concrete arch-shaped gravity dam in Indiana.

There are three basic designs for concrete dams: gravity, arch, and buttress types. Combinations of these types are also possible. For instance, a gravity dam may be constructed in an arch-like shape, and buttresses may be used to help support it. Roller compacted concrete construction techniques are becoming an economic alternative to traditional concrete construction methods.

2.3 CONSTRUCTION MATERIALS

Most dams in Indiana are embankment dams constructed with soil fill material. The fill should be a cohesive soil (clay) with adequate strength characteristics to withstand the long term forces to which it will be subjected.

Figure 2-9 Typical earth embankment dam with riprap shore protection.

The types of materials that are used or found on embankments are often dictated

Figure 2-10 Grass-lined emergency spillway.

by the dam design or anticipated usage of the embankment, including access and roadway requirements. Gravel, rock (riprap), concrete, asphalt, articulated concrete blocks, and grass are often used to help stabilize the embankment surfaces. Most materials normally require a subbase treatment before placement. For example, rock placed on an embankment for wave action will require a proper filter material beneath it to prevent subsurface soil erosion. Concrete and asphalt should also have a proper subbase for drainage and bearing support, usually consisting of a coarse aggregate (gravel). Except for soil, most of these materials are used for embankment slope protection, roadways, etc.

Figure 2-11 Riprap slope protection on an embankment dam.

The embankment surfacing must be capable of withstanding the worst-expected conditions (rainfall, wave action, high winds, vehicular and foot traffic) to prevent damage to the underlying dam structure. If the dam contains an impervious core, adequate protective material should be provided on the surface to protect the core from damage by frost heave and from the formation of desiccation cracks at the top of the impervious core. In all cases, it is preferable that the material used to cover the embankment is a material that will not shrink or crack when dried out. This will prevent the formation of drying cracks in the embankment and the possible infiltration of reservoir water or surface runoff into the dam's cross section through the surface cracking. If the embankment is a homogeneous earth fill dam constructed of cohesive soil material (common in Indiana), a layer of topsoil is usually placed over the fill to cover the cohesive soil and promote grass growth.

Figure 2-12 Public road on dam crest.

Embankment soil fill is usually covered with grasses or riprap to prevent erosion. If the dam is a rockfilled structure, or a zoned embankment dam, the slopes and crest will usually be rock. Benches are often used on either the upstream or downstream slopes to reduce overall slope angles, or grades, and to help control stormwater runoff.

When access across the dam is needed only for maintenance operations that can be scheduled during favorable weather conditions, no special crest surfacing is required. In these cases, the crest surfacing is usually composed of soil materials placed during original embankment construction. If access across the dam is required under all weather conditions for the safe and routine operation of the dam, or for public travel, the crest should be surfaced with gravel or pavement. If the dam is a rockfilled structure, the crest may also be rock. Again, if access is required, the top of the rockfill is often smoothly finished or gravel is placed on the crest to provide a smooth roadway. Any modifications to retrofit a dam with an access road may require a proper engineered design and approval from state and local agencies.

2.4 GEOLOGICAL SETTING

The geological setting is a very important factor when designing dams, or when trying to troubleshoot problems or safety deficiencies. It is crucial that the inspector fully understand the geological features and conditions of the site to better assess problems and deficiencies. For example a dam located in a glacial outwash area is likely to be sitting on permeable granular materials, which would tend to transmit water (seepage) in the foundation and abutment areas.

Site-specific information obtained from a geotechnical exploration program will better define and qualify the subsurface conditions in a given geological setting. For example, a dam located in a karstic geological setting will require subsurface exploration data to better define the physical parameters and extent of typical solution features (voids and joint openings) in the foundation, abutment, and spillway areas of the structure.

All dams should be assessed in light of both the local site and regional geological conditions. In addition to knowing the construction history of the dam and appurtenant structures, the inspector or the inspection team should have knowledge of the potential geologic factors that may influence the performance and safety of an existing dam. For example, successful filling and sustainability of the impoundment are directly linked to the geological setting. Part 4 contains a fact sheet to help dam owners gain a better understanding of their geological conditions.

Indiana dams typically consist of embankments made of earth materials over soil or rock foundations with auxiliary channel spillways through natural ground. As such, dams in specific regions tend to have similar characteristic or potential problems, some of which were not considered in the original design but later emerged as geologic hazards.

Many existing dams were constructed without appropriate methods and/or components to adequately address the existing geologic materials or the geologic conditions. Some of the dam safety deficiencies, as listed below, are a result of the dam builder not recognizing the physical characteristics and technical problems of certain geologic materials/conditions and implementing an appropriate design to mitigate the problems.

- Settlement, instability and/or cracking of the dam may reflect weak foundation conditions or unsuitable soil materials in the embankment.
- Seepage and/or leakage at the downstream toe or abutment/groin areas are frequently associated with the permeability characteristics of the underlying bedrock or soil.
- Natural hazards such as landslides, subsidence, and seismic events may quickly cause a component of the dam to fail leading to an uncontrolled breach.

2.5 THE WATERSHED

The watershed is the area that is located upstream of the dam that contributes water to the reservoir. The size of the watershed, shape of the watershed, soil and surface conditions, topographic features, land use, the amount and intensity of rainfall, and vegetative conditions are the principal factors that will determine how much water will drain into the reservoir and the time it will take for the water to reach the reservoir. The water that flows across the land surface and ends up in the reservoir is commonly known as runoff. Generally, the larger the watershed is, the greater the amount of runoff will be. It is also easy to see that the smoother the land surface is, the greater the runoff will be. For this reason, urban development in the watershed will typically increase the amount of runoff that will enter the reservoir. Urban development usually consists of construction of buildings, roads, parking lots, sidewalks, piping, ditches, etc. All of these features make the land surface smoother and more impermeable, resulting in more runoff. Installing stormwater collection and conveyance ditches and piping will make the runoff travel quicker and reach the reservoir sooner. This will also tend to increase the peak rate of runoff entering the reservoir. Therefore, more urban development in the watershed will result in more water entering the reservoir.

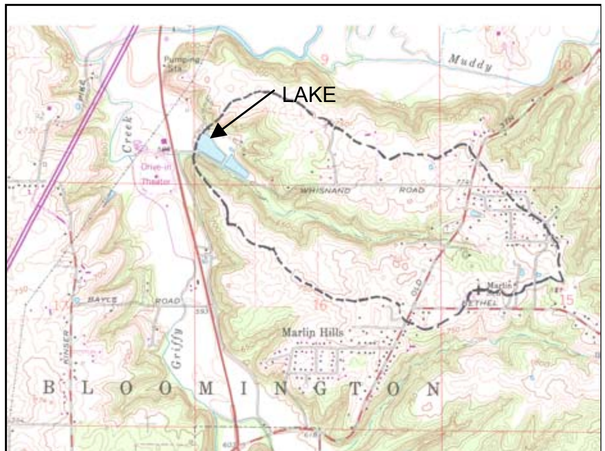

Figure 2-13 USGS quadrangle map depicting approximate watershed and divide for a small reservoir.

The limits of the watershed are defined by the watershed divide; a line that divides the area whose runoff flows toward the reservoir from land whose runoff flows away from the reservoir. The watershed divide is determined by the topographic characteristics, and generally, it follows topographically high points. Hydrologists typically draw the location of the watershed divide on a topographic map, such as a detailed site survey or a USGS quadrangle map. Defining the divide is usually the first step in analyzing the watershed characteristics.

Dam owners must monitor urban development in the watershed and fully understand how the development can affect the reservoir and dam. If a dam and its spillways were constructed before the urban development occurs, and if they were not designed to account for the development, the dam may not be able to safely pass the increased amount of runoff that will result. The ability of the dam and its spillways to accommodate flood events diminishes as the amount of urban development increases. If significant new development occurs, new hydrologic and hydraulic analyses should be performed to determine the impact the new development has on the dam. Larger spillway structures may have to be installed to maintain the safety of the dam and downstream property. The best way to monitor watershed development is through a combination of visual inspection and review of recent aerial photography. Many counties and the Indiana State Land Office periodically obtain aerial photography that is available to the public. Examples of upstream development projects that commonly affect the dam are the construction of another dam, a water conveyance system, or the construction of a new housing subdivision.

Generally, the more water that enters the reservoir from the watershed, the higher the water level will rise behind the dam. And in turn, the higher the reservoir rises in the dam, the higher the discharge will be through the spillway(s). Through a combination of reservoir storage and spillway discharge, a dam must be able to handle the watershed runoff that enters the reservoir from the design storm event without overtopping the dam or adversely affecting the spillway or it outlet structures.

2.6 DOWNSTREAM DEVELOPMENT ISSUES

In Indiana, the hazard classification of dams is based on the potential for loss of life and property in the area downstream of the dam. High hazard dams are those that do pose a threat if the dam were to fail, regardless of how safe the dam and its appurtenant works are at the present time. A dam's hazard classification can change at anytime due to potential development in the downstream area. Therefore, just because a dam is not classified as a high hazard dam when it is designed and built does not mean it may not someday become a high hazard dam. The implications of a high hazard classification are increased monitoring and reporting obligations, as well as increased risk and liability for the dam owner.

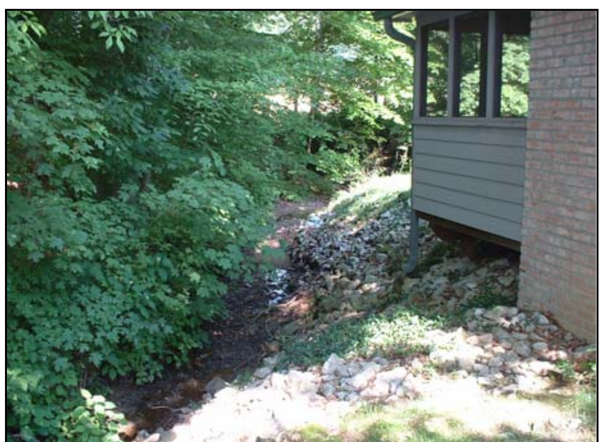

Figure 2-14 This house, located along the receiving stream downstream of a dam, represents poor planning, development, and technical judgment.

The dam owner must continually monitor downstream development throughout the life of the dam and reservoir. And unless the dam owner has ownership of the land downstream, he/she has no control over settlement and development in the potential inundation zone. Government entities usually do not have the means or authority to limit development below dams in all of the dam-failure inundation areas.

The dam owner must have a good idea of the dam-failure inundation zone below the dam to be able to monitor development within that zone. This is usually accomplished by obtaining professional help to perform a dam breach analysis. The breach analysis provides an estimate of the elevations to which flood waters would rise and the distance downstream that would be impacted in the event of a catastrophic dam failure. The inundation area is plotted on a map of the downstream area, typically a USGS 7 ½ minute quadrangle map, along with the location of any development within the zone. The list of downstream residents with their telephone numbers is often plotted on the map for easy reference in the case of emergencies. Sometimes it is obvious that development has occurred in the inundation zone without performing a breach analysis, especially when the development is close to the dam in the low-lying areas.

The best way to monitor downstream development is through a combination of visual inspection and review of recent aerial photography. It is the dam owner's responsibility to protect downstream landowners from harm no matter when the development occurs. Therefore, the dam owner should make downstream inspections part of the normal dam operating plan.

2.7 STORAGE AND RELEASE OF WATER

A dam is constructed for the purpose of storing water; the storage of water poses a risk to downstream areas and a liability to the dam owner. Therefore the ability of the dam to retain the water is of prime importance.

Uncontrolled release of water, such as seeps, piping, or embankment overtopping, is usually undesirable and must be monitored and controlled to prevent a dam breach failure. Some concrete dams are designed to be overtopped; in these cases the spillway is over the top of the dam. Overtopping of an earth dam is usually a disastrous event and should be prevented at all costs. Water seeping through or under the dam is undesirable, but usually occurs at most dams since the soil used to construct dams and their foundations is permeable. Therefore, plans and controls are usually implemented to control the seeping water and discharge it safely without endangering the dam. The dam owner is responsible and liable for any damage that might occur because of an uncontrolled release of stored water.

The spillways and outlets works are designed for controlled release of the reservoir water, during sunny day operation and flood events. Spillways are the normal, day-to-day release mode; outlets are designed to drawdown the reservoir below the spillway elevation. Outlet works, also called drawdown works or drains, are used for various reasons:

- quickly lower water level if dam failure is an issue
- lower water level for dam repairs or maintenance
- regulate downstream flow
- provide irrigation water
- drive hydro-machinery

Whatever the release mechanism, dam owners must design spillways, outlet works, of seepage discharge facilities to avoid impacts to downstream receiving waters, land adjacent to the receiving water, or the dam itself. The release structure must be designed to avoid excessive flows and flow velocities that could inundate or erode buildings, roads, or other structures in the downstream areas. Typically, spillways should be designed so that the discharge during flood events is no greater than the flows before the dam was built. On the other hand, outlet facilities may need to be operated on a continual basis to provide irrigation water or to maintain minimum stream flows for downstream users. Dam owners must be aware of riparian rights of downstream landowners and water users so that they don't diminish the available of water to those entities.

Figure 2-15 Valve for drawdown works located in bottom of riser structure; the valve stem should be extended to the top of the riser.